CONSTRAINTS ON COSMIC-RAY ORIGIN THEORIES FROM TEV GAMMA-RAY OBSERVATIONS

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ABSTRACT

If supernova remnants (SNRs) are the sites of cosmic-ray acceleration, the associated nuclear interactions should result in observable fluxes of TeV gamma-rays from the nearest SNRs. Measurements of the gamma-ray flux from six nearby, radio-bright, SNRs have been made with the Whipple Observatory gamma-ray telescope. No significant emission has been detected and upper limits on the >300 GeV flux are reported. Three of these SNRs (IC443, gamma-Cygni and W44) are spatially coincident with low latitude unidentified sources detected with EGRET. These upper limits weaken the case for the simplest models of shock acceleration and energy dependent propagation.

INTRODUCTION

It is generally believed that cosmic rays with energies less than ~ 100 TeV originate in the galaxy and are accelerated in shock waves in shell-type SNRs. This hypothesis is supported by several strong arguments. First, supernova blast shocks are one of the few galactic sites capable of sustaining the galactic cosmic ray population against loss by escape, nuclear interactions and ionization energy loss assuming a SN rate of about 1 per 30 years and a 10% efficiency for converting the mechanical energy into relativistic particles. Second, models of diffuse shock acceleration provide a plausible mechanism for efficiently converting this explosion energy into accelerated particles with energies $\sim 10^{14} - 10^{15}$ eV and naturally give a power-law spectrum similar to that inferred from the cosmic ray data after correcting for energy dependent propagation effects. Finally, observations of non-thermal X-ray emission in SN1006 (Koyama, et al., 1995) and IC443 (Keohane, et al., 1997) suggest the presence of electrons accelerated to ~ 100 TeV and ~ 10 TeV respectively.

If SNRs are sites for cosmic ray production, there will be interactions between the accelerated particles and the local swept-up interstellar matter. Drury, Aharonian and Volk (1994) (DAV) and Naito and Takahara (1994) have calculated the expected gamma-ray flux from secondary pion production using the model of diffusive shock acceleration. The expected intensity (DAV) is

$$F(>E) = 9 \times 10^{-11} \left(\frac{E}{1\text{TeV}}\right)^{-1.1} \left(\frac{\theta E_{SN}}{10^{51}\text{erg}}\right) \left(\frac{d}{1\text{kpc}}\right)^{-2} \left(\frac{n}{1\text{cm}^{-3}}\right) \text{cm}^{-2}\text{s}^{-1} \qquad (1)$$

where E is the photon energy, θ is the efficiency for converting the supernova explosion energy, E_{SN}, into accelerated particles, d is the distance to the SNR and n is the density of the local ISM.

We report on the results of observations of six nearby SNR (W44, W51, gamma-Cygni, W63, Tycho and IC443) by the Whipple Observatory's high energy gamma-ray telescope situated on Mount Hopkins in southern Arizona. The telescope (Cawley et al., 1990) employs a 10 m diameter optical reflector to focus Čerenkov light from air showers onto an array of 109 photmultipliers covering a 3 degree field of view. By making use of distinctive differences in the lateral distribution of gamma-ray induced showers and hadronic induced showers, images can be selected as gamma-ray like based on their angular spread. The determination of the incident direction of the selected gamma-ray like events is accomplished by making use of the orientation, elongation and asymmetry of the image. Monte Carlo studies have shown that gamma-ray images are a) aligned towards their source position on the sky b) elongated in proportion to their impact parameter on the ground and c) have a cometary shape with their light distribution skewed towards their point of origin in the image plane. Results on the Crab Nebula indicate that the angular resolution function for the telescope using this technique is a Gaussian with a standard deviation of 0.13 degrees. (Lessard et al., 1997). A combination of Monte Carlo simulations and results on the Crab Nebula indicate that the energy threshold of the technique is 300 GeV and the effective collection area for a point source located at the center of the field of view is $2.1 \times 10^8 \text{cm}^2$ and is reduced for offset sources (Lessard et al., 1997).

The analysis of data from extended sources involves binning the event arrival directions. We define the source region for the SNR by a circular aperture which matches the maximum extent of the radio shell (Green, 1995) plus twice the width of the angular resolution function to account for the smearing of the edge of the remnant. The number of gamma-ray candidate events is obtained by subtracting the number of events in the OFF-source observations from the number of events in the ON-source observations.

RESULTS

The observations were made over three observing seasons, from 1993 to 1996. Two dimensional images of the excess events for the Crab Nebula (which was deliberately offset from the center of the camera, to demonstrate the veracity of the technique) and the SNR W51 are shown in Figure 1. In each frame, the statistical significance is displayed in grayscale. The black contours are from the 4850 MHz radio survey by Condon et al., 1994, showing the extent of the radio shell. The circle shows the circular aperture used to derive the excess counts from the entire remnant (see Table 1).

Of the six remnants observed, W 51 showed the greatest excess at an offset location which is spatially consistent with hard x-ray emission and peak radio intensity. More data are required to determine if this excess is signicant. No significant excess has been recorded for the other remnants and 99.9% confidence upper limits on the flux have been calculated (see Table 1). The upper limit assumes uniform emission from the remnant in the absence of *a priori* knowledge of a more defined emission region.

DISCUSSION

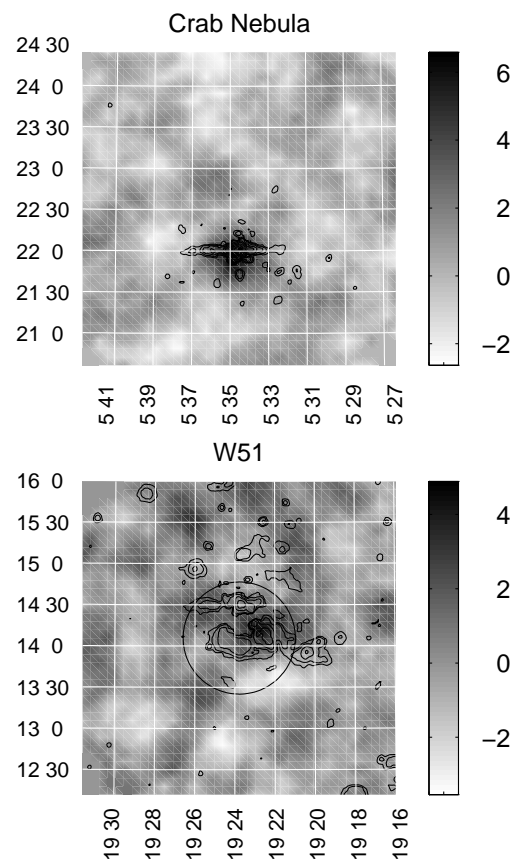In Figure 2 the Whipple upper limits and EGRET data (Es-

Fig. 1: Observations of the Crab Nebula and W51. We have applied a boxcar smoothing method which maximizes the point source sensitivity. The statistical significance of the excess selected events is shown in grayscale. The overlayed contours are proportional to the 4850 MHz radio intensity.

for the remaining) are compared with an $E^{-2.1}$ extrapolation of the EGRET data using the contribution to the gamma-ray spectrum from secondary pion decay as derived by Buckley et al. (1997) using the model of DAV. The upper dotted curve assumes a source spectrum of $E^{-2.1}$ and a reasonable maximum value of the product $E_{SN}\theta/d^2$ used in the model. The lower dotted curve assumes a source spectrum of $E^{-2.3}$ and a reasonable minimum value of the product $E_{SN}\theta/d^2$.

We interpret our results in the context of two hypotheses, (1) that the EGRET data gives evidence for acceleration of cosmic ray nuclei in SNR and that the observed gamma-ray emission comes not from primary electrons but from nuclear interactions of cosmic rays with ambient material or (2) that the EGRET flux is produced by some other mechanism.

Under the assumption that the contribution from electron bremsstrahlung and inverse Compton (IC) scattering are neglible, it is reasonable to compare the high energy gamma-ray upper limits to an extrapolation of the integral EGRET fluxes using the model by DAV. In the case of gamma-Cygni, IC443 and W44 the Whipple upper limits lie a factor of $\sim$ 25, 10 and 10 respectively below the extrapolation and require either a spectral break or a source spectrum steeper than $E^{-2.5}$ for gamma-Cygni and $E^{-2.4}$ for IC443.

Another plausible explanation for the results is that the EGRET flux is produced by high energy electrons accelerated in the vicinity of pulsars. If this is the case, then the Whipple upper limits must be compared with the *a priori* model predictions. There is enough uncertainty in the parameters of the SNR that the upper limits are not in strong conflict with these predictions, but it is still strange that in these objects which show strong evidence for interactions with molecular clouds (corresponding to the upper dotted curve) in no case is there an observable TeV gamma-ray flux. Evidence of an X-ray
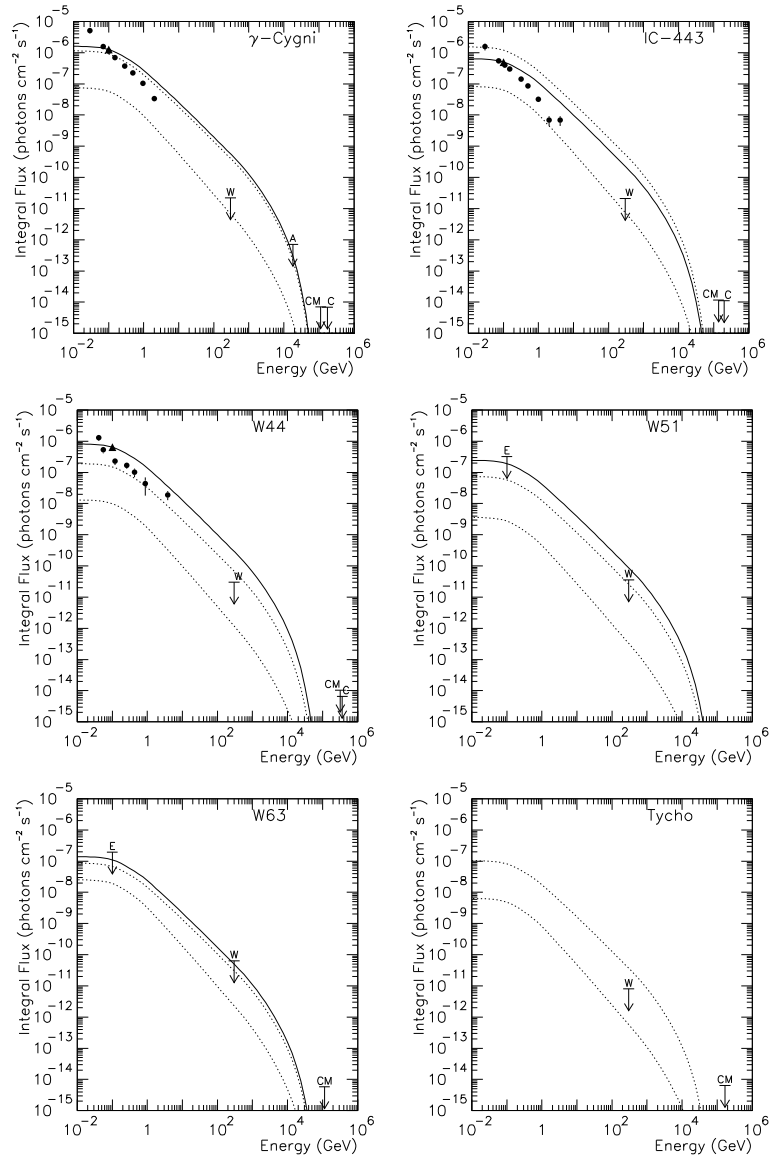

Fig. 2: Whipple upper limits shown along with EGRET integral fluxes, and integral spectra. These are compared to extrapolations from the EGRET integral data points (solid curves), as well as a conservative estimate of the allowable range of fluxes from the model of DAV (dotted curves). Also shown are CASA-MIA upper limits from Borione et al., 1995, CYGNUS upper limits from Allen et al., 1995, and the AIROBIC upper limit from Prosch et al., 1996.

point source embedded in gamma-Cygni (Brazier et al., 1996) and IC443 (Keohane et al., 1997) and the observation of a pulsar, B1853+01, in W44 (Wolszczan, et al. 1991), all provide support to a pulsar origin for the EGRET flux.

Table 1: Results of Observations.

Source Name	Pointing α, δ (1950)	Aperture Radius (deg)	ON Source Counts	OFF Source Counts	Total Time (min)	Upper Limit $\times 10^{-11}$ (cm^{-2}s^{-1})
W44	18:53:29, 01:14:57	0.55	450	426	360.1	3.0
W51	19:21:30, 14:00:00	0.68	619	559	468.0	3.6
γ-Cygni	20:18:59, 40:15:17	0.76	1040	1104	560.0	2.2
W63	20:17:15, 45:24:36	1.05	452	501	140.0	6.4
Tycho	00:22:28, 63:52:11	0.29	315	302	867.2	0.8
IC443	06:14:00, 22:30:00	0.64	1565	1522	1076.7	2.1

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